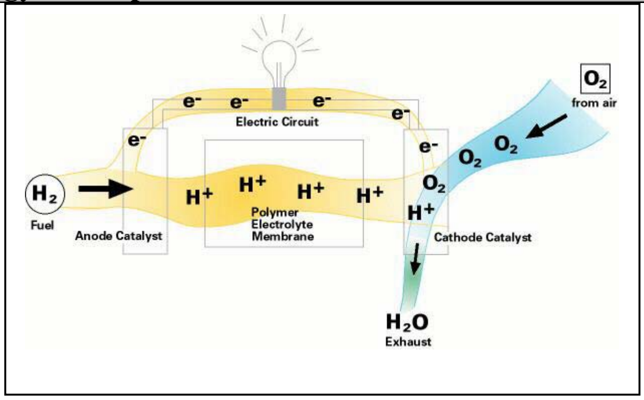
Fuel Cells

Technology Description



A fuel cell is an electrochemical energy conversion device that converts hydrogen and oxygen into electricity and water. This unique process is practically silent, nearly eliminates emissions, and has no moving parts.

System Concepts

- Similar to a battery, fuel cells have an anode and a cathode separated by an electrolyte.
- Hydrogen enters the anode and air (oxygen) enters the cathode. The hydrogen and oxygen are separated into ions and electrons, in the presence of a catalyst. Ions are conducted through the electrolyte while the electrons flow through the anode and the cathode via an external circuit. The current produced can be utilized for electricity. The ions and electrons then recombine, with water and heat as the only byproducts.
- Fuel cell systems today typically consist of a fuel processor, fuel cell stack, and power conditioner. The fuel processor, or reformer, converts hydrocarbon fuels to a mixture of hydrogen-rich gases and, depending on the type of fuel cell, can remove contaminants to provide pure hydrogen. The fuel cell stack is where the hydrogen and oxygen electrochemically combine to produce electricity. The electricity produced is direct current (DC) and the power conditioner converts the DC electricity to alternating current (AC) electricity, for which most of the end-use technologies are designed. As a hydrogen infrastructure emerges, the need for the reformer will disappear as pure hydrogen will be available near point of use.

Representative Technologies

- Fuel cells are categorized by the kind of electrolyte they use.
- Alkaline Fuel Cells (AFCs) were the first type of fuel cell to be used in space applications. AFCs contain a potassium hydroxide (KOH) solution as the electrolyte and operate at temperatures between 60 and 260°C (140 to 500°F). The fuel supplied to an AFC must be pure hydrogen. Carbon monoxide poisons an AFC, and carbon dioxide (even the small amount in the air) reacts with the electrolyte to form potassium carbonate.
- Phosphoric Acid Fuel Cells (PAFCs) were the first fuel cells to be commercialized. These fuel cells operate at 190-210°C (374-410°F) and achieve 35 to 45% fuel-to-electricity efficiencies LHV. Commercially-validated reliabilities are 90-95%. The largest market barrier is cost ($4,500 - $5,500/kW), which is why PAFCs are being phased out of commercial production
- Proton Exchange Membrane Fuel Cells (PEMFCs) operate at relatively low temperatures of 70-100°C (150-180°F), have high power density, can vary their output quickly to meet shifts in power demand, and are suited for applications where quick start-up is required (e.g., transportation and power generation). The PEM is a thin fluorinated plastic sheet that allows hydrogen ions (protons) to pass through it. The membrane is coated on both sides with highly dispersed metal alloy particles (mostly platinum) that are active catalysts.
- Molten Carbonate Fuel Cell (MCFC) technology has the potential to reach fuel-to-electricity efficiencies of 45 to 60% on a higher heating value basis (HHV). Operating temperatures for MCFCs are around 650° C (1,200°F), which allows total system thermal efficiencies up to 50% HHV in combined-cycle applications. MCFCs have been operated on hydrogen, carbon monoxide, natural gas, propane, landfill gas, marine diesel, and simulated coal gasification products.

- Solid Oxide Fuel Cells (SOFCs) operate at temperatures up to 1,000°C (1,800°F), which further enhances combined-cycle performance. A solid oxide system usually uses a hard ceramic material instead of a liquid electrolyte. The solid-state ceramic construction enables the high temperatures, allows more flexibility in fuel choice, and contributes to stability and reliability. As with MCFCs, SOFCs are capable of fuel-to-electricity efficiencies of 45% to 55% LHV and total system thermal efficiencies up to 85% LHV in combined-cycle applications.

Technology Applications

- Fuel cell systems can be sized for grid-connected applications or customer-sited applications in residential, commercial, and industrial facilities. Depending on the type of fuel cell (most likely SOFC and MCFC), useful heat can be captured and used in combined heat and power systems (CHP).
- Premium power applications are an important niche market for fuel cells. Multiple fuel cells can be used to provide extremely high (more then six-nines) reliability and high-quality power for critical loads.
- Data centers and sensitive manufacturing processes are ideal settings for fuel cells.
- Fuel cells also can provide power for vehicles and portable power. PEMFCs are a leading candidate for powering the next generation of vehicles. The military is interested in the high-efficiency, low-noise, small-footprint portable power.

Current Status

- Fuel cells are still too expensive to compete in widespread domestic and international markets without significant subsidies.
- PAFC – More than 250 PAFC systems are in service worldwide, with those installed by ONSI having surpassed 2 million total operating hours with excellent operational characteristics and high availability.

Economic Specifications of the PAFC (200 kW)

Expense	Description	Cost
Capital Cost	1 complete PAFC power plant	$850,000
Installation	Electrical, plumbing, and foundation	$40,000
Operation	Natural gas costs	$5.35/MMcf
Minor Maintenance	Service events, semiannual and annual maintenance	$20,000/yr
Major Overhaul	Replacement of the cell stack	$320,000/5 yrs

Source: Energetics, Distributed Energy Technology Simulator: Phosphoric Acid Fuel Cell Validation, May 2001.

PEMFC – Ballard's first 250 kW commercial unit is under test. PEM systems up to 200 kW are also operating in several hydrogen-powered buses. Most units are small (<10 kW). PEMFCs currently cost several thousand dollars per kW.
SOFC – A small, 25 kW natural gas tubular SOFC systems has accumulated more than 70,000 hours of operations, displaying all the essential systems parameters needed to proceed to commercial configurations. Both 5 kW and 250 kW models are in demonstration.
MCFC – 50 kW and 2 MW systems have been field-tested. Commercial offerings in the 250 kW-2 MW range are under development.

Some fuel cell developers include:

Acumentrics Corporation
Anuva Corporation
Avista Laboratories
Ballard Power Systems, Inc
Ceramatec
Electrochem, Inc.
FuelCell Energy
Hydrogenics Corporation
IdaTech
McDermitt Technologies, Inc.
Mitsubishi Electric Corporation
ONSI Corporation (IFC/United Technologies)
Plug Power, LLC
Siemens Westinghouse Power Corporation
Solid State Energy Conversion Alliance
Toshiba Corporation
UTC Fuel Cells
Ztek Corporation

Fuel Cell Type	Electrolyte	Operating Temp (°C)	Electrical Efficiency (% HHV)	Commercial Availability	Typical Unit Size Range	Start-up time (hours)
AFC	KOH	260	32-40	1960s		
PEMFC	Nafion	65-85	30-40	2000-2001	5-250 kW	< 0.1
PAFC	Phosphoric Acid	190-210	35-45	1992	200 kW	1-4
MCFC	Lithium, potassium, carbonate salt	650-700	40-50	Post 2003	250 kW-2 MW	5-10
SOFC	Yttrium & zirconium oxides	750-1000	45-55	Post 2003	5-250 kW	5-10

Sources: Anne Marie Borbely and Jan F. Kreider. *Distributed Generation: The Power Paradigm for the New Millennium*, CRC Press, 2001, and Arthur D. Little, Distributed Generation Primer: Building the Factual Foundation (multiclient study), February 2000

Technology History

- In 1839, William Grove, a British jurist and amateur physicist, first discovered the principle of the fuel cell. Grove utilized four large cells, each containing hydrogen and oxygen, to produce electric power which was then used to split the water in the smaller upper cell into hydrogen and oxygen.
- In the 1960s, alkaline fuel cells were developed for space applications that required strict environmental and efficiency performance. The successful demonstration of the fuel cells in space led to their serious consideration for terrestrial applications in the 1970s.
- In the early 1970s, DuPont introduced the Nafion® membrane, which has traditionally become the electrolyte for PEMFC.
- In 1993, ONSI introduced the first commercially available PAFC. Its collaborative agreement with the U.S. Department of Defense enabled more than 100 PAFCs to be installed and operated at military installations.
- The emergence of new fuel cell types (SOFC, MCFC) in the past decade has led to a tremendous expansion of potential products and applications for fuel cells.

Technology Future
• According to the Business Communications Company, the market for fuel cells was about $218 million in 2000, will increase to $2.4 billion by 2004, and will reach $7 billion by 2009. • Fuel cells are being developed for stationary power generation through a partnership of the U.S DOE and the private sector. • Industry will introduce high-temperature natural gas-fueled MCFC and SOFC at $1,000 -$1,500 per kW that are capable of 60% efficiency, ultra-low emissions, and 40,000 hour stack life. • DOE is also working with industry to test and validate the PEM technology at the 1–kW level and to transfer technology to the Department of Defense. Other efforts include raising the operating temperature of the PEM fuel cell for building, cooling, heating, and power applications and improve reformer technologies to extract hydrogen from a variety of fuels, including natural gas, propane, and methanol.

Sources: National Renewable Energy Laboratory. *U.S. Climate Change Technology Program. Technology Options: For the Near and Long Term.* DOE/PI-0002. November 2003; and National Renewable Energy Laboratory. *Gas-Fired Distributed Energy Resource Technology Characterizations*. NREL/TP-620/34783. November 2003.

Fuel Cells

Technology Performance

Source: Arthur D. Little (ADL) estimates, survey of equipment manufacturers.

Only industrial applications; table does not address residential/commercial-scale fuel cells.

		2000 Characteristics						2005 Characteristics					
		Installed Cost ($/kW)		Non-Fuel O&M (cents/kWh)		Electrical Efficiency (LHV)		Installed Cost ($/kW)		Non-Fuel O&M (cents/kWh)		Electrical Efficiency (LHV)	
Technology	Size Range (kW)	Low	High	Low	High	High	Low	Low	High	Low	High	High	Low
Low Temperature Fuel Cell (PEM)	200-250	2,000	3,000	1.5	2.0	40%	30%	1,000	2,000	1.0	1.8	43%	33%
High Temperature Fuel Cell (SOFC & MCFC)	250-1,000	NA						1,500	2,000	1.0	2.0	55%	45%

Source: Energetics, *Distributed Energy Technology Simulator: PAFC Validation,* May 2001.

	Size (kW)	Capital Cost	Installation (Site Preparation)	Operation Costs (Natural Gas)	Minor Maintenance	Major Overhaul
Installation of a commercially available PAFC	200	$850,000	$40,000	$5.35/MMcf	$20,000/yr	$320,000/5 yrs

Technology Performance

There have been more than 25 fuel cell demonstrations funded by the private sector, the government, or a cofunded partnership of both. The objectives for most have been to validate a specific technology advance or application, and most of these demonstrations have been funded by the Office of Fossil Energy.

This is a listing of the demonstrations that have taken place between 1990 and today that have been published. All of the demonstrations were deemed a success, even if the testing had to end before its scheduled completion point. All of the manufacturers claimed they learned a great deal from each test. All the OPT-funded demonstrations were used to prove new higher performance-based technology either without lower catalyst levels, metal separator plates, carbon paper in lieu of machined carbon plates, or new membrane materials. Only the Plug Power fuel cell tested for the Remote Power Project failed, due to an electrical fire.

Fuel Cell Type	**Company**	**Objective**
Phosphoric Acid Fuel Cell	UT Fuel Cells (IFC)/FE	12.5 kW prototype using a new membrane assembly. (60 units) 40 kW power plant (46 units) 100 kW prototype for Georgetown Bus. (2 units) Methanol 200 kW first manufacturing prototype for PC25 (4 units) including natural gas reformer
Phosphoric Acid Fuel Cell	IFC/OPT	200 kW hydrogen version of PC 25 without a reformer, lower cost assembly
Solid Oxide	Westinghouse/FE	2 MW SOFC at Toshiba for fuels and tubular geometry testing 100 kW plannar unit to test seals, Netherlands 250 kW hybrid(57/50) w/turbine SoCal Ed 250 kW tubular SOFC combined heat and power, Ontario Power
Molten Carbonate	Fuel Cell Energy/FE	250 kW 8,800 hours Danbury Ct. first precommercial prototype 3 MW four years to build, Lexington Clean Coal Project 2 MW San Diego failed early
Proton Exchange Membrane	Plug Power/OTT Plug Power/OPT	10 kW prototype for vehicles 50 kW unsuccessful 25 kW prototype for Alaska, integrated with diesel reformer 50 kW prototype for Las Vegas refueling station, integrated with natural gas reformer

Proton Exchange Membrane	IFC/OTT	10 kW prototype sent to LANL for evaluation 50 kW prototype sent to GM for evaluation, reduced Pt catalyst 75 kW prototype installed in Hundai SUV, prototype for all transportation devices
Proton Exchange Membrane	Schatz Energy Center/OPT	(3) 5 kW Personal Utility Vehicles, (1) 15 kW Neighborhood Electric Vehicle Palm Desert each incorporated different levels of Pt catalyst, different membranes, all hydrogen fueled 1.3 kW Portable Power Unit
Proton Exchange Membrane	Enable/OPT	(3) 100 W Portable Power Units to demonstrate radial design (2) 1.5 kW Portable Power Units incorporating the LANL adiabatic fuel cell design (1) 1 kW “air breather” design for wheelchair
Proton Exchange Membrane	Ballard: no DOE funds	(6) 250 kW 40 foot passenger buses, hydrogen fueled: 3 Chicago, 2 Vancouver, 1 Palm Desert (1) 100 kW powerplant for Ford “Think” car (1) 250 kW stationary powerplant new manufacturing design
Proton Exchange Membrane	Nuvera/OPT	3 kW powerplant using metal separator plate technology for Alaska evaluated by SNL and University of Alaska
Proton Exchange Membrane	Coleman Powermate/Ballard no DOE funds	(3) 1.3 kW precommercial prototype UPS systems, metal hydride storage, under evaluation at United Laboratories for rating
Proton Exchange Membrane	Reliant Energy	7.5 kW precommercial prototype of radial stack geometry with conductive plastic separator plates
Alkaline	Zetec	25 kW precommercial prototype to demonstrate regenerative carbon dioxide scrubber
Alkaline	Hamilton Standard/IFC	(100) 12.5 kW commercial units for NASA
Alkaline	Union Carbide	(2) 50 kW fuel cells for GM van and car